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Geospatial Analytics to Evaluate Point-of-Dispensing Sites for Mass Immunizations in Allegheny County, Pennsylvania

Kibri H. Everett, MS, **Margaret A. Potter, JD, MS**, **William D. Wheaton, MA**, **Sherrianne M. Gleason, PhD**, **Shawn T. Brown, PhD**, and **Bruce Y. Lee, MD, MBA**

RTI International, Research Triangle Park, North Carolina (Ms Everett and Mr Wheaton); University of Pittsburgh Graduate School of Public Health, Pittsburgh, Pennsylvania (Drs Potter and Gleason); Pittsburgh Supercomputing Center, Pittsburgh, Pennsylvania (Dr Brown); and Public Health Computational and Operations Research (PHICOR), University of Pittsburgh, Pittsburgh, Pennsylvania (Dr Lee)

Abstract

Context—Public health agencies use mass immunization locations to quickly administer vaccines to protect a population against an epidemic. The selection of such locations is frequently determined by available staffing levels and in some places, not all potential sites can be opened, often because of a lack of resources. Public health agencies need assistance in determining which n sites are the prime ones to open given available staff to minimize travel time and travel distance for those in the population who need to get to a site to receive treatment.

Objective—Employ geospatial analytical methods to identify the prime n locations from a predetermined set of potential locations (eg, schools) and determine which locations may not be able to achieve the throughput necessary to reach the herd immunity threshold based on varying R_0 values.

Design—Spatial location-allocation algorithms were used to select the ideal n mass vaccination locations.

Setting—Allegheny County, Pennsylvania, served as the study area.

Main Outcome Measures—The most favorable sites were selected and the number of individuals required to be vaccinated to achieve the herd immunity threshold for a given R_0, ranging from 1.5 to 7, was determined. Locations that did not meet the Centers for Disease Control and Prevention throughput recommendation for smallpox were identified.

Results—At R_0 = 1.5, all mass immunization locations met the required throughput to achieve the herd immunity threshold within 5 days. As R_0s increased from 2 to 7, an increasing number of sites were inadequate to meet throughput requirements.

Conclusions—Identifying the top n sites and categorizing those with throughput challenges allows health departments to adjust staffing, shift length, or the number of sites. This method has

Correspondence: Kibri H. Everett, MS, 3040 Cornwallis Road, PO Box 12194, Research Triangle Park, NC 27709 (keverett@rti.org).

the potential to be expanded to select immunization locations under a number of additional scenarios.

Keywords

location-allocation; mass vaccination; points of dispensing; synthetic populations

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The development of plans, policies, and standards to prepare for public health emergencies is one of the primary responsibilities of health departments. Preparations for responding to highly transmissible disease epidemics may involve emergently protecting the population with vaccines. In an effort to strengthen the effectiveness of the public health system to respond to various public health threats, the Centers for Disease Control and Prevention (CDC) created *Public Health Preparedness Capabilities: National Standards for State and Local Planning*[1] to guide health departments in their preparedness strategies and investments. One of the capabilities identified by CDC is Medical Countermeasure Dispensing, which includes the distribution of vaccines to at-risk populations in a short amount of time. Point-of-dispensing (POD) site locations are an important focus of emergency response planning, including planning for mass immunizations, when vaccines must be delivered to large numbers of people in a relatively short-time span. Methods for rapidly selecting such POD locations in an emergency are necessary because infectious diseases have disparate minimal coverage needs and in turn different requirements for “throughput”—the number of persons vaccinated per site per day.

Health departments take several factors into consideration when identifying the POD sites, where epidemic countermeasures are distributed in their territories. Many are illustrated in Figure 1. Two location-selection factors that can be addressed with geographic information systems (GIS) are travel time and travel distance minimization for residents to these mass immunization locations. In a disease outbreak, these are 2 measures that health departments would want to minimize because mass immunization locations that are close to their residents abate the impact of the emergency.[2] Although there are recommended standards for establishing immunization sites, there is a paucity of methods and tools for immunization site selection that incorporate travel distance.[3] Given a set of n predetermined potential immunization locations (often colocated with public high schools), the objective was to select the prime n sites to open while minimizing travel time and distance for residents. A secondary goal was to determine which of the n selected sites do not provide enough daily throughput to achieve local herd immunity based on a given reproductive rate, or R_0. According to the Pandemic and All-Hazards Preparedness Act,[4] the amount of funding that states receive from the US Department of Health and Human Services can be based on their level of preparedness; therefore, having tools and methods that allow them to locate mass immunization locations and allocate residents as part of the preplanning process is one way to demonstrate that progress is being made toward meeting the performance standards set forth under the Act.

Methodology

Allegheny County, Pennsylvania, where the city of Pittsburgh is located, served as the study area for this research. Although this study focuses on one jurisdiction, the methods employed can be applied to any geographic area. The Allegheny County Health Department has preselected 50 places in the county that could serve as mass immunization locations. Each site is an existing public high school in the county. High schools are recommended for several reasons,[5(Annex 3, p14)] the primary one being their capacity to handle large crowds because of the gymnasiums, auditoriums, and ample parking they have on-site. To determine the best number of locations to open in Allegheny County for travel time and distance minimization, a function in GIS known as *Location-Allocation*, was used. In a general GIS context, "Location" describes the process involved in finding the optimal locations for facilities (mass immunization locations) given a set of demand points. "Allocation" is the process of allocating demand points (households) to service areas that contain the facilities providing goods or services that satisfy the demand. In this type of analysis, the best facilities are located in such a way that the sum of all weighted costs between demand points and solution facilities is minimized.

The Location-Allocation uses heuristic methods that involve minimizing the distances from all facilities and each demand point.[2(p265)] Heuristic techniques are designed for solving a problem more quickly when classic methods are too slow, or for finding an approximate solution when traditional methods fail to find any exact solution. The procedure begins by finding the shortest-path allocation of demand points to solution facilities. An iterative process subsequently occurs to create an improved facility-demand point allocation. The method continues refining until the optimal location-allocation results are obtained. The algorithm uses the street network to allocate each demand point (household) to a facility (mass immunization location), taking into account several factors including the total number of facilities available, their geographic locations, and their distances to the demand points. The households used in the analysis were supplied from a synthetic population developed by Wheaton[6] for agent-based modeling with GIS. Synthetic households are placed across the landscape to match high-resolution population distribution data from the US Census Public Use Microdata Sample and are assigned to the closest road segment for use in the Location-Allocation process. The synthetic households accurately reflect the composition and distribution of real households.

The location-allocation analyses were processed at 5-site increments beginning with 30 (n=30, n=35 … n= 50) to obtain the most favorable sites that minimize time and distance for residents. The output generated from the process included a count of the demand points (total persons based on the synthetic population) allocated at each site. The first step in calculating throughput was to obtain the number needed to achieve a herd immunity threshold that would abate an epidemic, based on the R_0 of the epidemic. This threshold is equivalent to[7]

$$\text{Herd immunity threshold} = 1 - R_0/R_0.$$

Our previous modeling studies have suggested that failure to achieve the herd immunity threshold in a large region may not be enough to abate an epidemic.[8] If pockets of the populations or certain communities are not adequately protected, epidemics can continue. Therefore, to be conservative, we stipulated that each mass immunization location would aim to achieve the herd immunity threshold[9] among its catchment population.

Therefore, to tabulate the vaccination requirements, the population allocated at each site was multiplied by the proportion of the population needed to achieve herd immunity (33.3% for an epidemic with $R_0 = 1.5$ (corresponding to an influenza epidemic); 50% for an epidemic with $R_0 = 2$; 66.7% for an epidemic with $R_0 = 3$; 75% for an epidemic with $R_0 = 4$ (corresponding to an SARS epidemic); 80% for an epidemic with $R_0 = 5$; 83.3% for an epidemic with $R_0 = 6$; and 85.7% for an epidemic with $R_0 =7$ (corresponding to a smallpox epidemic). We also assumed that the county would have no more than a week (or 5 working days) to get its population protected. Thus, to get the daily throughput required to complete the immunizations within 5 days for each of these R_0s, the number needed to achieve the herd immunity threshold is divided by 5. The 5900 persons per day vaccination delivery estimate found in the CDC's *Smallpox Response Plan & Guidelines*[5(Annex 3, p8)] was used as a basis for determining which sites would exceed the throughput recommendation. (We used the smallpox throughput capacity as an example because none were readily available for other types of infectious epidemics). Any site with a throughput value exceeding this estimate was identified as a mass immunization location that would be over capacity.

Results

The Location-Allocation assigned each household in Allegheny County to one of the high school mass immunization locations. Residents assigned to selected facilities in and around the city of Pittsburgh are relatively close (1 or 2 miles) to their destination sites. Low-density areas, such as those outside the city, generally require longer travel times and distances, and thus, selected locations in those areas have people coming to them from longer distances. Figure 2 illustrates an example of the results obtained from selecting the best 30 sites from the complete set of 50. The large, white circles represent the 30 sites ideal for travel time and distance minimization. The smaller circles are the sites that did not get selected during the Location-Allocation analysis. The lines on the map, which illustrate the path between each household and its assigned immunization location, are symbolized in the legends to indicate the time in minutes and distance in miles that it would take for each household to travel to its associated site. For the vast majority of households, the travel distance is 5miles or less, and the travel time would be 5 minutes or less under normal traffic conditions. The large circles with the star indicate sites that would not meet the daily throughput required to complete immunizations for smallpox in 5 days.

The numbers of people assigned to each of the selected locations in each scenario were then analyzed to determine which of those selected sites were not able to meet the smallpox throughput recommendation of 5900 people per day. The Table contains a few records from the spreadsheet, including a location that was not selected (BRENTWOOD Senior High School) and one that was allocated but does not have sufficient throughput to meet allocated demand for $R_0 \geq 5$ (NORTH HILLS Senior High School). At an R_0 of 1.5, the population allocated at each location was sufficient for achieving herd immunity in each of the scenarios explored. The number of locations that exceeded the capacity needed for herd immunity increased with rising R_0s. When the top 30 sites of 50 were selected for travel time and travel distance minimization, there were 18 to 19 sites where demand exceeded capacity at the highest R_0s. As the number of selected sites increased, the number of sites that could meet this throughput increased. Even when all 50 sites were in operation, however, multiple locations were inadequate in meeting the demand to achieve herd immunity, beginning with an R_0 equal to 2 for travel time minimization and an R_0 of 3 for travel distance minimization. For these cases, health department officials could consider adding secondary immunization locations, such as nearby elementary or middle schools, or shifting residents to sites that were not initially selected for travel time or distance minimization. This could be viewed as a limitation of the model because the reallocation of residents from overloaded sites must be done as a secondary step.

Conclusion

The geospatial techniques employed in this study were used to identify the prime n mass immunization sites (from a previously determined set of sites) for travel time and travel distance minimization for residents in Allegheny County, Pennsylvania. When resources are limited, public health departments can use the Location-Allocation to select a subset of their locations such that the set of sites chosen minimizes travel time and travel distance. Although the function of the model was to allocate the universe of residents in the study area without instituting a "cap" at each site, health department officials are able to assess which locations would exceed capacity after the allocation is complete and then add resources to alleviate overburdened service areas.

The Location-Allocation is a heuristic and, as such, provides a useful tool for locating POD sites. Nevertheless, this method is subject to several limitations. First, it does not take into account qualitative variables, such as human behavior. Second, its results are static—meaning that any issues that arise during a dispensing process are not factored in. Third, although the methods are applicable to jurisdictions other than Allegheny County, potential issues with scalability in larger or smaller jurisdictions could exist.

Further research will involve the development of a Web-enabled tool that will aid in the decision-making process for selecting the most ideal sites for mass vaccination as well as for other POD site location needs—such as pharmaceutical dispensing. When implemented, the methods described in this study can be used to enhance a public health department's preparedness and demonstrate its progress toward meeting government standards and performance measures for medical countermeasure delivery during a disease outbreak or public health emergency.

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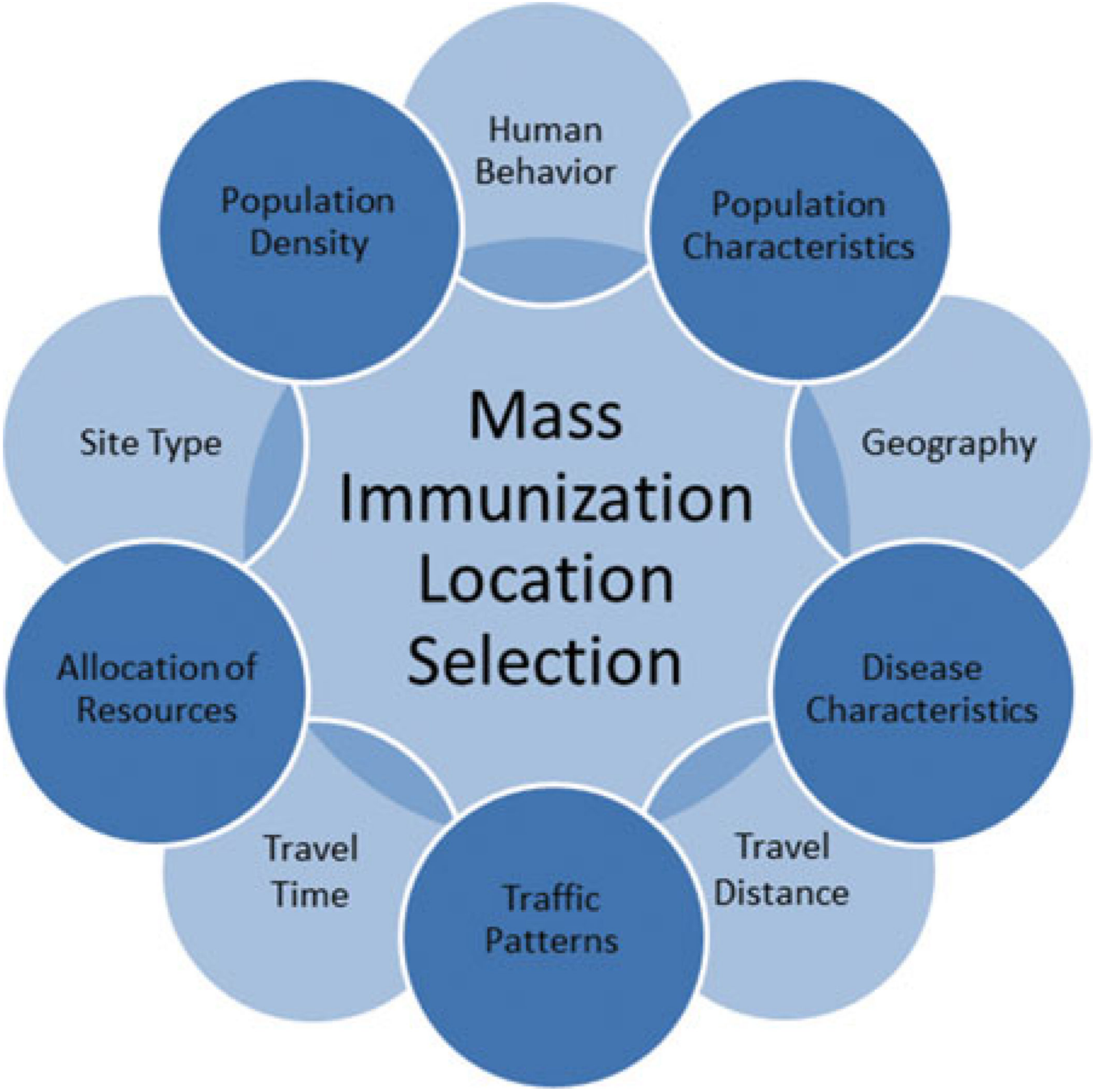

FIGURE 1.
Factors for Mass Immunization Location Selection

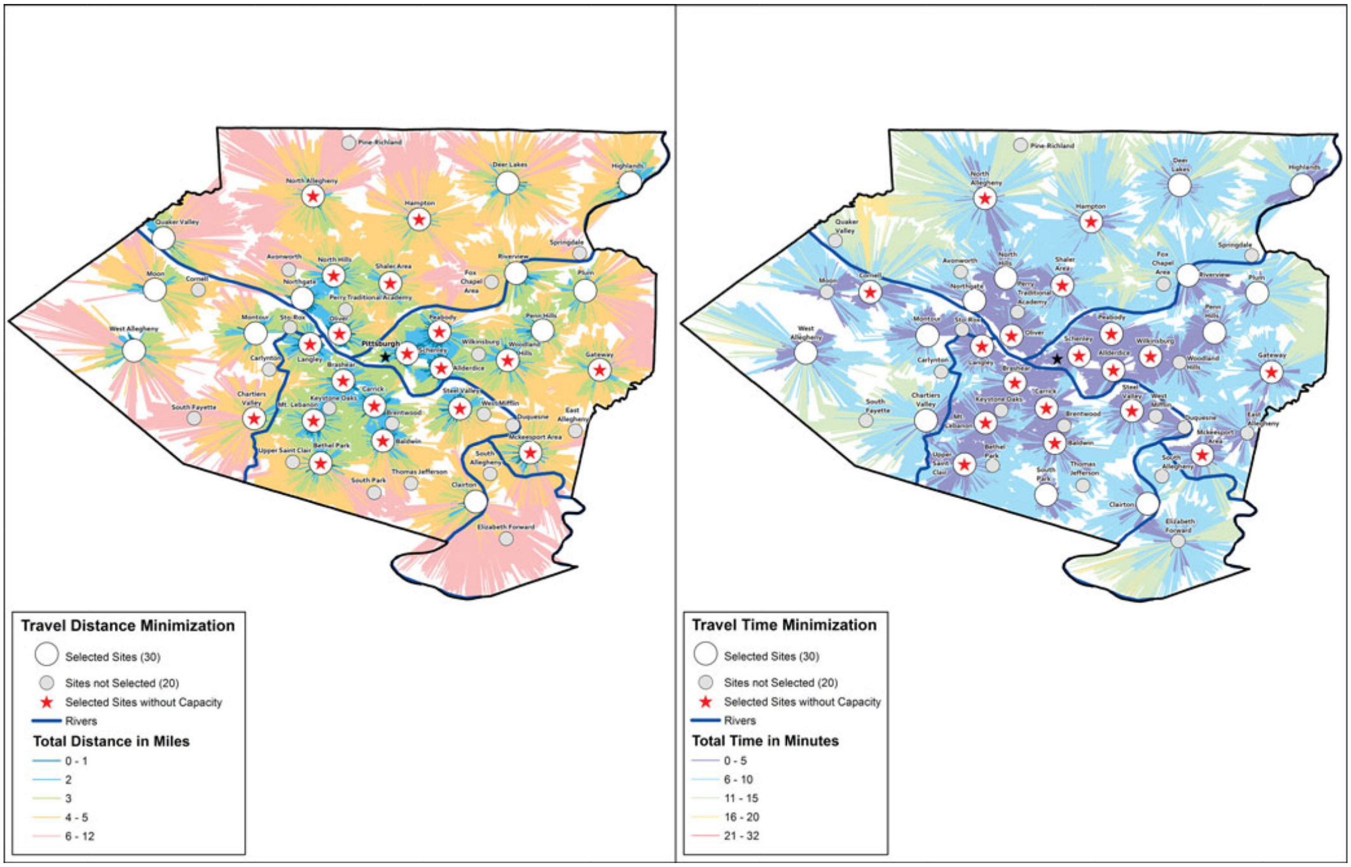

FIGURE 2.
Location-Allocation Results With 30 Sites Selected for Travel Time and Distance Minimization

TABLE

Analysis Results Showing Population Assigned, Selection Status, and Throughput for Five Mass Immunization Locations

	Number Needed to Achieve Herd Immunity for Each R_0 and Daily Throughput Required to Complete Immunizations in 5 Days							
		R_0 = 1.5	**R_0 = 2**	**R_0 = 3**	**R_0 = 4**	**R_0 = 5**	**R_0 = 6**	**R_0 = 7**
POD NAME		**33.3%**	**50.0%**	**66.7%**	**75.0%**	**80.0%**	**83.3%**	**85.7**
BRENTWOOD SENIOR HIGH SCHOOL[a]	Total Pop Allocated: 0	0	0	0	0	0	0	0
	Daily Throughput:	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CLAIRTON SENIOR HIGH SCHOOL[b]	Total Pop Allocated: 30,608	10,203	15,304	20,405	22,956	24,486	25,507	26,235
	Daily Throughput:	2,041	3,061	4,081	4,591	4,897	5,101	5,247
NORTH HILLS SENIOR HIGH SCHOOL[c]	Total Pop Allocated: 36,930	12,310	18,465	24,620	27,698	29,544	30,775	31,654
	Daily Throughput:	2,462	3,693	4,924	5,540	5,909	6,155	6,331
PLUM SENIOR HIGH SCHOOL[b]	Total Pop Allocated: 24,420	8,140	12,210	16,280	18,315	19,536	20,350	20,931
	Daily Throughput:	1,628	2,442	3,256	3,663	3,907	4,070	4,186
WEST ALLEGHENY HIGH SCHOOL[b]	Total Pop Allocated: 18,386	6,129	9,193	12,257	13,790	14,709	15,322	15,759
	Daily Throughput	1,226	1,839	2,451	2,758	2,942	3,064	3,152

[a] Not selected as one of the 30 centers and therefore, has no population assigned to it.

[b] Selected sites with adequate throughput for all R_0s.

[c] Selected site with inadequate throughput at $R_0 \geq 5$.